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AN INFRARED DETECTION APPARATUS

Field of the Invention

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The present invention relates to an infrared detection
apparatus for monitoring a field of view in order to
detect an adverse atmospheric condition. The apparatus
has particular application to detecting sulphur dioxide,
10   volcanic ash and wind-blown dust.

Background to the Invention

There are a number of adverse atmospheric conditions which
15   it would be desirable to detect. These include volcanic
ash, toxic gases such as sulphur dioxide gas and
wind-blown dust.

Volcanic ash is a hazard to jet aircraft, causing engines
20   to stall when ingested, scouring windows and the leading
edges of the wings and causing instrument malfunctions.
Damage to aircraft can be counted in the millions of
dollars. Most serious aircraft encounters with ash clouds
have been at cruise altitudes, but there is also a hazard
25   to aircraft at airports affected by volcanic ash. These
airports are usually close to an active volcano (e.g.
Anchorage and Kagoshima) but they can also be at some
distance from the source of the eruption due to
atmospheric transport that brings ash into the region.

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The cost of ash hazards to airport operations is not
known, but must be significant if the costs include those
due to delays to landings and take-offs as well as
re-routing costs incurred by airline operators. Currently
35   there are no regulatory requirements for airport operators
to provide warnings of ash hazards. Warnings are issued
based on information from volcano observatories,

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meteorological advisories and, in some cases, radar
observations of eruption columns. Radar information is
generally only reliable at the start of an eruption when
the ash cloud is thick and usually such information is
5   only available at airports in close proximity to an
erupting volcano. For airports distant from the source of
ash there are few direct observations available. Some
observations come from satellite systems and other sources
of information come from trajectory forecasts based on
10   wind data and cloud height information. Much of this
information is sporadic and untimely and there is a need
for better detection systems.

Other adverse atmospheric conditions include the toxic
15   gases emitted by volcanoes and industrial plants. Of
particular importance and abundance is sulphur dioxide
gas. This gas is colourless, but has a characteristic
pungent odour. Eye irritation and inflammation of the
respiratory tract occurs in relatively low concentrations.
20   Amounts of 6-12 ppm will cause immediate irritation of the
nose and throat. Long term exposure can exacerbate asthma
and can be dangerous to persons with preexisting
cardiopulminary diseases. Thus monitoring near to strong
sources of SO_2 (e.g. from industrial sources and at
25   volcanoes) is important as is longer term monitoring at
some distance from the source. Furthermore, SO_2 clouds
from volcanoes will react with water vapour, in the
atmosphere to produce sulphuric acid which can damage
aircraft. Accordingly, it would be desirable to be able
30   to warn aircraft of SO_2 clouds.

Wind-blown dust from desert regions or semiarid lands can
be a hazard to aircraft, reduces visibility significantly
and can cause eye and throat irritation to humans. Large
35   parts of the habitable earth are prone to dust storms,
including northern Africa, the Mediterranean islands,
southern Italy, Spain and France, southwestern USA,

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central and southern Australia, western parts of South
America, central China, Japan and south and north Korea
and the central deserts of Asia. The wind-blown dust can
also be transported long distances - dust from China has
5 been detected in North America. The dust consists of
nearly spherical particles of SiO_2 in concentrations that
can limit visibility to a few 10's of metres.
Accordingly, wind-blown dust can be a significant hazard
to aircraft, vehicles and the like.
10

Accordingly, it would be desirable to provide an apparatus
capable of monitoring one or more of these adverse
atmospheric conditions.

15 Summary of Invention

An infrared detection apparatus for detecting an adverse
atmospheric condition comprising:
          a plurality of filters corresponding to different
20 ones of a plurality of wavelengths and at least including
filters which enable the adverse atmospheric condition to
be detected;
          an infrared array, said infrared array producing
signals representative of infrared radiation reaching said
25 array;
          radiation control means for controlling the
infrared radiation received by the infrared array, the
radiation control means including means for changing the
filters so that said infrared array can produce wavelength
30 signals representative of infrared radiation from each of
said wavelengths corresponding to the adverse atmospheric
array, and means for enabling said infrared array to
produce calibration signals for each wavelength signal;
          calibration means for performing a calibration of
35 each wavelength signal to correct for radiation from the
infrared detection apparatus on the basis of at least the
corresponding calibration signal to thereby produce a

calibrated wavelength signal representative of radiation
from the region of sky; and

output means for producing an output indicative
of the presence of the adverse atmospheric condition in
5   the region of sky based on the calibrated wavelength
signals.

Preferably the apparatus also includes correction means
for correcting the calibrated signals for water vapour
10   absorption and/or viewing angle effects

Preferably, the correction means comprises a pre-computed
look-up table (LUT). Typically, the LUT is based on
off-line detailed radiative transfer calculations which
15   account for the effects of water vapour absorption and for
viewing geometry for each of the preferred filtered
infrared wavelengths.

Preferably, the means for enabling said infrared array to
20   produce calibration signals comprises a shutter having
infrared emissivity which is high in each of said
wavelengths.

Preferably, said radiation control means controls said
25   shutter to shut prior to each wavelength measurement to
thereby enable said array to produce a calibration
measurement corresponding to the preceding wavelength
measurement.

30   Preferably, the calibration means also calibrates on the
basis of a pre-calibration.

Preferably, the calibration is performed on the basis of a
calibration equation of the form $R = a \times C + b$, where R is
35   the calibration wavelength signal, C is the wavelength
signal, and a and b are coefficients.

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Preferably, the calibration means alters the coefficient of the calibration equation on the basis of the calibration signal.

5   Typically, calibration coefficients are calculated for each filter and for each pixel of the infrared array.

Preferably, said output means outputs temperature difference images derived from at least two wavelengths.

10

In one embodiment said output means produces an alarm if the adverse atmospheric condition is present.

Preferably, said alarm is produced if the temperature
15 differences exceeds a predetermined value.

The algorithm for enabling the output means is dependent on the atmospheric condition. We have determined algorithms suitable for a number of atmospheric
20 conditions.

Where the atmospheric condition is sulphur dioxide, the algorithm is based on the temperatures $T_{8.6}$, $T_{10.0}$, $T_{11.0}$ and $T_{12.0}$ at four wavelengths, 8.6 μm, 10.0 μm, 11.0 μm and 12.0
25 μm.

Preferably said algorithm involves determining a first temperature difference $\delta T_1 = T_{8.6} - T_{10.0}$, a second temperature difference $\delta T_2 = T_{11.0} - T_{12.0}$, adding the
30 differences δT_1, δT_2 to obtain a third temperature difference δT_3 used as the basis to determine whether SO_2 is present.

Where said atmospheric condition is volcanic ash, it is
35 preferred that said algorithm is based on a temperature difference between two wavelengths, $T_{11.0}$ and $T_{12.0}$.

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Preferably an alarm for volcanic ash is activated if $\delta T_{va} = T_{11} - T_{12} > \Delta T_E$, where ΔT is a temperature threshold.

Preferably, where the atmospheric condition is wind-blown
5   dust the algorithm is $\delta T_{dust} = aT_{8.6} + bT_{11} + cT_{12}$ where a, b and c are constants.

Brief Description of the Drawings

10   A preferred embodiment of the invention will now be described with reference to the accompanying drawings in which:

Figure 1a is a block diagram that shows the apparatus of a preferred embodiment;
15   Figure 1b is a schematic diagram which shows the camera portion of the apparatus of the preferred embodiment;

Figure 2 shows the filter functions of the apparatus;
20   Figure 3 shows the variation of elevation angle with temperature difference;

Figures 4a and 4b show variation of elevation angle with temperature difference for two different channel differences;
25   Figure 5 shows the apparatus of the invention viewing a sulphur dioxide plume;

Figure 6 shows an image produced of SO_2 plume using the apparatus of the present invention;

Figure 7 shows a view of a plume of SO_2 with an
30   explosion;

Figure 8 shows an image of an explosion produced using an ash algorithm;

Figure 9 shows a different image for the sky when there is no ash or sulphur dioxide present;
35   Figure 10 is a temperature histogram for the image of Figure 9;

Figure 11 illustrates the Gaussian and

thresholding technique for setting an ash alarm;

Figures 12a and 12b show a raw and a calibrated image respectively, illustrating the dramatic effect calibration has on the identification of features;

5   Figure 13 is a map of test sites;

Figure 14 shows the proximity of Tavurvur volcano to the airport;

Figure 15 has ash and visible images taken from Rababa;

10   Figure 16 shows the alarm histogram for Figure 15;

Figure 17 has ash and visible images from Matupit;

Figure 18 shows the alarm histogram for Figure 15   17;

Figure 19 is a view of an eruption from Rabaul Volcanological Observatory;

Figure 20 is a graph of an alarm time-series;

Figure 21 has ash and visible images from Hamamas 20   Hotel; and

Figure 22 shows the alarm histogram for Figure 22.

Description of the Preferred Embodiment

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The preferred embodiment provides an infrared detection apparatus for monitoring infrared signals from a field of view in order to detect an adverse atmospheric condition such as volcanic ash, sulphur dioxide or wind-blown dust.

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Figure 1a is a block diagram of the infrared detection apparatus of a preferred embodiment. The infrared detection apparatus 30 comprises an infrared camera 110, a processor 140 and satellite modem 160 for transmitting 35   signals from the infrared detection apparatus 130 to a monitoring station 150.

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The camera portion 110 of infrared detection apparatus 130
is shown in Figure 1. The camera 110 has a filter wheel
housing 2, a window 3 that is transmissive in the infrared
(e.g. a Germanium window), a shutter 4, a filter wheel
5   cover 6 and a filter wheel. Infrared array housing 8
contains an infrared array 9 and a signal processing unit
10.

Output from the signal processing unit 10 is on signal
10   lines 11a which have an Ethernet interface to the computer
140 so that it can process the signals. Lines 11b allow
the shutter control signals to be received by the infrared
detection apparatus 130 from the computer 140 and also for
equipment temperature measurements passed to the computer
15   140. The temperature measurement corresponds to the
temperature of the shutter 4 and are obtained by a contact
thermometer (not shown).

The infrared detection apparatus 130 operates by
20   monitoring infrared signals from a field of view (e.g. a
region of sky) being monitored at up to five pre-defined
wavelengths. While the wavelengths are monitored, the
wavelengths which are used in detecting the adverse
atmospheric condition depend on the adverse atmospheric
25   condition which is being monitored. The central
wavelength and wavelength intervals are given in Table 1.
It will be appreciated that a band of wavelengths surround
a central wavelength, but for convenience the terms
"wavelength" or "channel" are used herein to refer to the
30   central wavelength and surrounding band unless the context
implies otherwise. The infrared radiation measured by the
camera 110 is linearly proportional to the resistance
change in the detector, which is recorded and logged by
the signal processing unit 10. In the preferred
35   embodiment the infrared array is an uncooled
microBolometer staring array of 320 x 240 elements
sensitive to radiation in the 6-14 μm wavelength interval

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is used to detect filtered radiation. The detection
apparatus uses a filter wheel to filter radiation. The
radiation from the field of view is focussed onto the
array by means of focussing optics in the form of lens 5
5   and the field of view is a cone of up to 90 degrees.

As indicated above, in the preferred embodiment, the
infrared array will be an uncooled microBolometer array of
dimensions at least 320 x 240 elements, but 640 x 480
10   elements is also possible. There is a trade-off between
the number of elements, cost and maximum spatial
resolution per pixel for a fixed optical arrangement. The
microBolometer operates on the principle that a
temperature change produced by radiation falling on the
15   detector produces a linear resistance change in the
material. There are three types of bolometer in
commercial use: metal, semi-conductor and super-conductor.
In the preferred embodiment either VOx and Si-based
semi-conductor bolometers can be used as these are
20   available commercially. However, it would be possible to
use a cooled array with a cryogenic cooler with the
ground-based device if the performance criteria cannot be
met with an uncooled array.

25   The camera 110 can be used to obtain measurements at up to
five separate wavelengths to be filtered and also can have
a single broadband channel depending on what atmospheric
condition is being monitored. The camera 110 uses a
filter wheel mounted with circular interference filters.
30   Table 1 provides the information for the selection of the
filters.

The filters are 50 mm diameter germanium/ZnSe multi-layer
interference filters mounted on a rotating wheel and
35   driven by a stepper-motor. (But, smaller or larger
diameter filters may be used depending on the field of
view required and the focusing power of the optics).

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Thus, the filter wheel provides a radiation control means for controlling the infrared radiation received by the infrared array 9.

5   The array 9 has a nominal noise temperature of no less than ≈50 mK in the broadband channel. To achieve appropriate temperature sensitivity in the narrow band channels, frame averaging is employed. Table 1 shows the theoretical noise equivalent temperatures (NEΔT's)
10 expected for various frame averaging values in 5 narrow wavelength bands or channels and one broadband channel 20. Thus five narrow band channels centered around 7.3 μm, 10.1 μm, 11 μm and 12 μm are shown in Figure 2 as items 21, 22, 23, 24 and 25 respectively. It will be appreciated by
15 those skilled in the art that the precise central wavelengths and band passes may vary, and that the wavelengths and band passes shown in Table 1 are nominal and used here as indicative working wavelengths.

Band	High	Low	NEΔT	4	8	16	32	64
7.3	7.05	7.55	1346	673	476	337	238	168
8.6	8.35	8.85	890	445	315	223	157	111
10.1	9.85	10.35	643	322	227	161	114	80
11	10.75	11.25	657	329	232	164	116	82
12	11.75	12.25	900	450	318	225	159	113
8-14	8	14	65	33	23	16	11	8

20 Table 1: Noise equivalent temperatures (NEΔT, mK) for different amounts of frame averaging.

Table 1 shows noise equivalent temperatures over 1, 4, 8, 16, 32 and 64 frames. It will be seen that for each
25 doubling in the number of frames the noise equivalent temperature is reduced by approximately 30%.

In order to produce an output indicative of the presence of an adverse atmospheric condition, the raw data produced
30 by the infrared array is calibrated (or corrected).

The apparatus of the preferred embodiment is calibrated so
that the processing means can produce corrected radiance
values which then can be used to produce scene

5   temperatures which can subsequently be processed using an
algorithm specific to the atmospheric condition in order
to determine the presence of the adverse atmospheric
conditions. The calibration process consists of a
pre-calibration and a field calibration. The calibrations

10   correct for radiation from the infrared detection
apparatus. In particular the field calibration is
required in order to correct for changes in the radiation
from the infrared detection apparatus during operation.
Thus, the field calibration technique is a key feature

15   which allows sufficiently accurate determination of the
presence (or not) of the adverse atmospheric conditions.

Figure 12a shows a typical scene where the image is
constructed from the raw signals, without calibration.

20   Figure 12b shows the same scene this time after
calibration and conversion to temperature units. Aspects
of the scene not visible in the raw data are now clearly
noticeable in the calibrated data. For example, roof 200
is now visible.

25

The camera 110 provides raw digital counts as output of
detector array 9 that have also had some corrections
applied. These counts can be related to the scene
radiance through a linear calibration process, and scene

30   then to temperature through use of the Planck function.

A two point blackbody pre-calibration procedure was
developed which uses the output from the detector array 9
corresponding to two cooled and heated blackbody cavities

35   placed in front of the lens. The calibration equations

are:

$$R_{i,c} = a_i C_{i,c} + b_i, \qquad (1)$$
$$R_{i,h} = a_i C_{i,h} + b_i, \qquad (2)$$

5   where, the subscripts c and h to the cold and hot
       blackbodies, and i refers to the channel or filter number
       being used, R = radiance, C = counts and a and b are
       coefficients corresponding to a gain and an offset
       respectively. In practice the camera 110 views over a
10   band of wavelengths and the response of the camera 110
       (detector and filter) as a function of wavelength must be
       known. The radiance is therefore related to the scene
       temperature, T_s, through,

15                      $R_i = \int_{\lambda_1}^{\lambda_2} B[\lambda, T_s]F(\lambda)d\lambda, \qquad (3)$

       where λ is wavelength, F is the response of the system,
       and B is the Planck function.

20   To convert from the calibrated radiances to scene
       temperature, Equation (3) is inverted. This is a
       non-linear problem which requires a minimisation
       procedure. A series of look-up tables were generated that
       give radiances equivalent to a series of pre-specified
25   temperatures. Once the measured radiance is known by
       combining (1) and (2), the look-up table is searched and
       interpolated (if necessary) to determine the closest scene
       temperature. The procedure is accurate to 10 mK over the
       range of observable temperatures 220 K to 330 K.
30
       The procedure to pre-calibrate the camera 110 is:

       • the camera is allowed to acclimatise to the environment
         for a period of several minutes – this ensures that the
35   camera lens is neither heating up nor cooling down,

       • the filter wheel is commanded to move the appropriate

filter into position,

- the cold blackbody is moved in front of the lens,

5
- several frames (up to 24 in the current configuration) are acquired, averaged and stored on the camera memory,

- the hot blackbody is moved into view (in front of the lens),

10
- several frames (up to 24 in the current configuration) are acquired, averaged and stored on the camera memory,

- the process is repeated for the next filter,

15
- after completing all required filters the camera is commanded to send the data across a communications line to a computer.

20 A separate set of calibration coefficients a_i, b_i is developed for each pixel within the 320 x 240 image. Towards the edges of the image the quality of the calibration degrades due to image distortions and non-uniformity of the blackbodies. The blackbody
25 temperature is measured in one place on each blackbody and non-uniformity of the temperature field will occur to some degree.

The pre-calibration procedure was repeated several times
30 and average look-up tables were generated. Typically the pre-calibration is performed in the laboratory and not done in the field. A field calibration technique is used to alter the coefficients to account for the optics (particularly the lens) that may be heating up or cooling
35 down and thus be at a different temperature to its value when calibrated in the laboratory. This causes an off-set in the measured signals. Our innovative field calibration

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procedure makes use of a single shutter measurement just
before measurements are taken at each wavelength. The
shutter fills or slightly overfills the field of view of
the instrument and provides a uniform radiation source to
5   the detector. The temperature of the side of the shutter
facing the lens is continuously monitored using a contact
temperature probe. The shutter side facing the lens is
blackened so that its infrared emissivity is high
(exceeding 0.98) and uniform across the region 6-14 μm.
10   In the field, the calibration is performed by making a
single measurement of the shutter, followed by a
measurement of the scene and then application of the
calibration equations and shutter measurement which
accounts for the off-set generated by any change in
15   temperature of the lens or other radiating surfaces in
front of the detector.

The raw data is also calibrated for background atmospheric
conditions and viewing angle by the calibration means.
20   That is, the temperature differences on a single channel
will vary depending on the channel measured.

In clear and cloudy skies when there is no ash or SO_2
present, water vapour causes differential absorption of
25   radiation in the atmospheric window between 6-14 μm. Thus
when comparing two channels there will be a temperature
difference. Theoretical calculations and modelling
studies indicate that this difference will be negative
when the camera views the sky above the horizon. The
30   exact value of the difference depends on the amount of
water vapour, but also on the path length that the
radiation traverses through the atmosphere. Figure 3
shows the theoretical variation of the temperature
difference (11-12 μm) with elevation for a cloudless
35   atmosphere containing about 3 cm of precipitable water.
At low elevation angles the temperature difference is
slightly negative, but gets progressively more negative

until at around 60 degrees elevation when the difference
decreases slowly. A consequence of this behaviour is that
it is not possible to set a constant threshold for
deciding whether infrared difference images contain ash
5   affected pixels. Figure 4a shows the difference as
determined from measurements made at Saipan. The
variation with elevation angle mimics the theoretical
behaviour. The same effect with elevation can be seen for
8.6-12 μm temperature differences (Fig. 4b), except that
10   after 60 degrees the difference starts to increase rather
than decrease. This is not seen in the modelling results,
and more data are required to determine the cause of this
effect. These data show more variation than the
theoretical studies because the scene also contains clouds
15   and unmodelled water vapour variations. Nevertheless, the
temperature difference decreases with elevation angle in
all cases studied and agrees with the theoretical
behaviour.

20   When the variations and temperature difference are
understood, temperature difference can be corrected in
order to correct the output images so that the output
temperature difference images correctly reflect the
presence of the adverse atmospheric condition being
25   detected.

The algorithms and temperature differences which are used
depend on the adverse atmospheric condition that is being
monitored for in the field of view.
30

SO_2 Algorithm

Figure 5 shows a digital image of the camera viewing
towards the Etna volcano in the background with a plume of
35   SO_2 30 emitted from the crater. An SO_2 image produced by
the apparatus within 30 minutes of the digital image is
shown in Figure 6. The colour scale 22 is drawn to

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indicate the amount of SO$_2$ in the plume - from yellow,
indicating low amount, to brown, indicating high amounts.

The background to the images comprises light areas of blue
5   and green indicating a colder background whereas the
bottom of the image which is dark in colour represents the
ground.   These areas are labelled 33 and 34 respectively.
The left vertical axis represents elevation in degrees and
the horizontal axis represents Azimuth.   The images are
10   typically produced in colour as indicated above however it
will be appreciated that appropriate grey scale images can
also be produced.   The colour images make it easier to
discern the plumes from the background.

15   An SO$_2$ index is based on a 4-channel algorithm, while the
temperature difference images utilize all 5 channels, the
4 narrow band channels and a wide band channel.   The SO$_2$
index is derived by:

20   (1)   forming the temperature difference between a
channel centred at 8.6 μm and a channel centred at 10.0μm,
label this difference as δT_1,
(2)   forming the temperature difference between a
channel at 11.0 μm and a channel centred at 12.0 μm, label
25   this difference as δT_2,
(3)   adding temperature differences δT_1 and δT_2, label
this δT_3, subtracting a reference value that depends on the
viewing elevation of the camera, and has a typical range
of 1-3°C, label this δT_4 to get the final temperature
30   difference (this is the SO$_2$ index).

The displayed temperature difference image is produced by
scaling δT_4 and overlaying this scaled image into the
broadband image so that all pixels in the δT_4 temperature
35   difference image with a scaled value in the range 1-32 are
preserved and all pixels outside this range are replaced
by image pixel from the broadband filter image.   A

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suitable colour table is then attached to the image and a reference grid and scale are incorporated.

The resulting image (Figure 6) shows SO_2 plume 30 in yellow
5   to brown colour, water vapour (in various degrees of amount) in grey colours, the background (colder) sky as blue and green 33 and topographic features (mountain, ground, trees etc., which are generally warmer than the plume) as dark grey to black 34.
10

The SO_2 index derived in this way is linearly related to the temperature difference. In reality there is a nonlinear relation between the temperature differences and the SO_2 amount measured in atm cm or other suitable units.
15 This relation is of the form:

$$u = ln[\alpha \delta T_4 + \beta],$$

However, the linear approximation used to derive the SO_2
20 index is a reasonable approximation to the nonlinear algorithm and is sufficient for the purposes of the embodiments of the present invention.

It would also be appreciated that any appropriate
25 graphical representation can be used. However, the use of a colour graded output scale is preferred because this allows continuous monitoring of the atmospheric hazard.

Volcanic Ash Algorithm
30

A volcanic ash algorithm which can be used with the apparatus may be stated as:

$$\delta T_2 = T_{11} - T_{12} > \Delta T_t,$$

35

where the subscripts 11 and 12 refer to the channel central wavelengths and ΔT_t is a temperature threshold that

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depends on the water vapour content of the atmosphere and on the viewing elevation angle of the camera. The nominal value for ΔT_t is 0°C. Data (pixels) with values above the threshold are regarded as volcanic ash. Data (pixels)
5   below the threshold are regarded as not volcanic ash.

In testing, the apparatus was also able to capture discrete explosions from the Stromboli Volcano. An example of this is shown in Figure 7. In the case of the
10   explosion, the pyroclastic material is mostly volcanic hot rocks, cinders and ash and reveals itself as grey to black colours 41 when the SO_2 algorithm is used. An SO_2 plume 42 is clearly shown. In contrast when the ash algorithm is used, that is, by taking temperature differences using two
15   channels, specifically δT_2, the image shown in Figure 7 is obtained. The colour scale now shows positive temperature differences in shades of orange and red, and negative differences as blue to yellow. In this case the algorithm identifies the hot rocks and cinders as positive
20   differences 40 (high ash content), and resuspended ash as slightly negative (similar to the material on the surface of the mountain slopes). The sky has markedly negative differences.

25   <u>Wind-Blown Dust Algorithm</u>

Desert dust has a high silica (SiO_2) content and when small particles (diameters less than 10 μm) are suspended in the atmosphere they disperse infrared radiation in a similar
30   fashion to volcanic ash particles. Consequently, the algorithm used to identify ash in the atmosphere can also be used to identify wind-blown dust. Dust storms are a frequent and global phenomenon. Most of the dust is confined to the boundary layer - the part of the
35   atmosphere closest to the surface and generally not extending more than 5 km upwards. Occasionally, large dust storms can be transported vast horizontal distances

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(may 1000's of kilometres) and be lifted to heights
greater than 5 km. Dust storms have been identified using
passive infrared radiation from satellites. The dust
algorithm differs from the ash algorithm in one important
5   aspect. Since it is unlikely that wind-blown dust will
contain any appreciable amounts of SO_2 gas (the reverse
being true for ash), a channel at 8.6 μm, can be used in
conjunction with the 11 and 12 μm channels. The dust
algorithm thus uses three channels rather than two. The
10 form of the algorithm is:

$$\delta T_{dust} = aT_{8.6} + bT_{11} + cT_{12},$$

where the subscripts 8.6, 11 and 12 refer to the central
15 wavelengths (in μm) for each channel and *a, b* and *c* are
constants. The nominal values of these constants are:
a = 1, b = 1 and *c = -1*.

It will be appreciated that it will not always be
20 convenient or appropriate for someone to monitor the image
data from the apparatus. Accordingly, an automated
algorithm can be developed in order to initiate an alarm
either so the person can be alerted to the need to monitor
the alarm or to send data from the apparatus 130 to a
25 monitoring station 150. This alarm is based on analysis
of the difference images produced in accordance with the
algorithms. However, it will be appreciated that the
images do not actually have to be produced in order for
the alarm to be triggered, that is, the data can be
30 processed to determine whether an alarm condition is met.
An example of an alarm algorithm suitable for volcanic ash
is described, however it is to be appreciated that other
alarm algorithms can be developed.

35 An automated alarm algorithm has been developed minimise
the requirement for operator intervention of the infrared
image data and/or to trigger the transmission of an image

to the users - i.e. to transmit the image data to
monitoring station 150 when there is sufficient reason for
a user to inspect the image. The algorithm or 'alarm' is
based on a histogramming technique that takes into account
5   the viewing elevation and the amount of water vapour in
the atmosphere. In the present embodiment there are
320 x 240 image pixels in a single temperature difference
image (ΔT_1, ΔT_2, ΔT_3). Due to cloud movement, noise,
calibration errors and sensitivity limitations, some
10   pixels will appear anomalous when there is little or no
hazard within the image. The histogramming technique
accounts for these anomalies.

In general the structure of these anomalies is very
15   different to that expected from an ash cloud. However, on
a pixel-by-pixel basis it is impossible to determine
whether the signal is due to a camera anomaly or due to a
real ash signature. Analysis of the images obtained from
Anatahan volcano in conditions where ash was known to be
20   present suggests that analyses of structure in the images
can be used to set a threshold or alarm to indicate the
presence of ash. To demonstrate how this can be done we
first consider a set of images obtained in conditions
where there was no ash or SO_2. Figure 9 shows an image
25   obtained in ash/SO_2-free conditions viewing with an
elevation of 20 degrees above the horizon. The
temperature differences of this image range from -15 K to
+10 K and these are usually represented on a colour scale.
Most ambiguity will typically exist in the region of -0.5
30   K to +0.5 K. Thus grey-coloured pixels in the temperature
difference image may be regarded as *marginal*, in terms of
detectability. In our temperature difference images this
region is -0.5 K to 0.5 K and a grey sale is used to
represent such pixels in practice. In Figure 9 there are
35   some grey-coloured pixels, but the majority of the pixels
are yellow, green to blue indicating negative temperature
differences and hence normal conditions (i.e. clear skies

or water/ice meteorological clouds). The 2-dimensional
histogram of this image is shown in Figure 10. The same
temperature range and colour scale are used for the
histogram. From theoretical and modelling calculations we
5   expect pixels that are ash contaminated to have positive
differences. But, their actual value depends on viewing
conditions, particularly the viewing elevation, and also
the amount of water vapour in the path. Accordingly, we
have determined that a threshold value of 0 K for ash is
10   appropriate under most conditions. Figure 9 was obtained
at 20 degrees elevation and as the field of view of the
infrared camera is roughly 24 degrees in the vertical
direction, some parts of the image view land surfaces.
The histogram in Figure 10 has prominent peaks at roughly
15   -1 K 51 and -5 K 50 which correspond to clouds and clear
skies, respectively. In this case the least negative peak
has a tail that includes some positive pixels. In the
corresponding image (Figure 9) these pixels are due to
viewing features that are low on the horizon and include
20   ground targets. Such 'anomalies' are difficult to isolate
in an automated manner and could give rise to *false alarms*
if a straightforward pixel thresholding technique were
employed.

25   The scheme chosen to automatically determine whether an
image has detected ash is a statistically based method.
This is the method of choice because by the nature of the
problem there is often going to be a distribution of
pixels that can be flagged as ash, within an image that
30   has many pixels that are definitely ash or definitely not
ash. In addition, because of the likelihood that pixels
will contain mixtures, a simple threshold and binary
decision process would be inappropriate.

35   The histogram shown in Figure 10 has two prominent peaks
with a spread of pixels around these peaks. If the
detection apparatus 130 viewed a target of constant

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temperature (e.g. a uniform cloud or the clear sky), then simply because of the fact that the camera has a wide field of view and there is water vapour absorption along the differing paths to the target, the resulting
5   difference image would be non-uniform. In practice it is unlikely that the sky would present a uniform target and even less likely that a cloud would by perfectly uniform. The combination of these effects leads to a natural spread in the histogram of the temperature differences, with a
10   central peak corresponding to the mode temperature difference. For a relatively uniform scene the peak would be high and the spread (or standard deviation of the distribution) would be low. We have selected a Gaussian distribution to model the distribution. The Gaussian
15   distribution in the mathematical terms is,

$$G(\Delta T) = A_0 \exp-\left\{\frac{(\Delta T - \mu_{\Delta T})}{\sigma_{\Delta T}}\right\}^2 ,$$

where ΔT is the temperature difference, $\mu_{\Delta T}$ is the mean
20   temperature difference, $\sigma_{\Delta T}$ is the standard deviation, and A_0 is the maximum frequency, which occurs when $\Delta T = \mu_{\Delta T}$. Each of the peaks ($i = 1 ... n$) within the frequency distribution (histogram plot) is assumed to be centred at $\mu_{\Delta T,i}$ with a spread of $\sigma_{\Delta T,i}$. A set of Gaussian distribution
25   is fitted to the frequency distribution data and the parameters, $A_{0,i}$, $\mu_{\Delta T,i}$, and $\sigma_{\Delta T,i}$ derived. The linear combination of these distributions is the model-fit to the data.

30   The fit for the histogram data shown in Figure 10 is shown in Figure 11. Three Gaussians were used in the fit:

Parameter	i=1	i=2	i=3
$A_{0,i}$	74.2%	24.9%	0.9%
$\mu_{\Delta T,i}$	-4.24 K	-0.84 K	-0.67 K
$\sigma_{\Delta T,i}$	+1.49 K	+0.33 K	+0.08 K

The fit to the distribution although not perfect, it is
sufficient for setting the alarm for the image. A
threshold Gaussian is set with a mean and standard
deviation derived from modelling. This threshold Gaussian
5   is compared with the *n*-Gaussian data-fit. The region
between the pixels bounded by the *threshold Gaussian* mean
value, and the overlap region between the two Gaussians
(the *threshold* and the data-fit) is calculated. This area
(or number of pixels) is subtracted from the number of
10   pixels that exceed the *threshold Gaussian* mean value and
lie within the data-fit Gaussian (see Fig. 11).

The ratios,

$$\left(\frac{P_i - P_{o,i}}{P_i} \right)$$

15

$$R_I = \frac{A_{o,i}}{\sum_{j=1}^{n} A_{o,j}}$$

20   where $P_{o,i}$ is the number of overlap pixels for Gaussian *i*,
P_i is the number of pixels that exceed the *threshold* mean,
and $A_{o,i}$ are the maxima for the Gaussian fits. The purpose
of normalising by the maximum is to ensure that more
weight is given to distributions that have well-defined
25   and dominant peaks.

It will be appreciated that any number of different
statistical techniques can be used in order to determine
whether sufficient numbers of the pixels relate to the
30   atmospheric condition being monitored to warrant the
generation of alarm.

Experimental Results

35   During the period 26-30 November 2003 CSIRO experimentally
operated the detection apparatus at the site of an
erupting volcano near Rabaul town, in west New Britain,

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Papua New Guinea (PNG). The volcano, Tavurvur has
ash-rich explosions every 10-30 minutes, with plumes that
extend several hundred meters above the crater,
approximately 400 m above sea level. A large number of
5   infrared images were obtained at various distances from
the crater and employing a variety of viewing angles. The
purpose of this field work was to obtain reliable ash
images to prove the concept of ash detection from a
ground-based platform.
10

The results indicate that the detection apparatus can
image ash plumes and clouds and clearly discern these from
meteorological clouds. Results are best at closest
proximity to the ash cloud, but good results were obtained
15   at distances greater than 5 km from the active crater.
The ash alarm algorithm was also tested in an autonomous
manner overnight from a distance of ~8 km.

Measurement Sites

20

Figure 13 shows the locations of the measurement sites
(six in all) used to image the ash-rich eruptions from
Tavurvur. They are listed in Table 2.

Site label	Site name	Distance from crater (km)
A	Hamamas Hotel	3.7
B	Rabaul airport (old)	3.0
C	Rababa ("hot springs")	1.8
D	Matupit village	2.5
E	RVO	8.0
F	CPL Mill	7.4

25   Table 2. Site labels, names and locations used to make
measurements of the ash-rich plumes and clouds from

- 25 -

Tavurvur volcano (labeled Tavurvur in Fig. 13).

Tavurvur has been active since a major eruption took place
in September 1994 which devastated the town of Rabaul and
5   destroyed the airport. A new airport, Tokua, has been
constructed and is located about 20 km southwest of
Tavurvur. With the crater still active, flights in and
out of Tokua only take place in daylight hours and not at
all if the winds move the ash towards the airport runway.
10   Figure 14 shows a digital photograph taken from the runway
at Tokua. A plume 60 from Tavurvur is noticeable in the
background.

The Rabaul Volcanological Observatory (RVO) operates on a
15   hill overlooking the active crater and at about 8 km
distance from it. Economic pressures in PNG have meant
that only limited resources are available at RVO for
operating geophysical equipment and power failures are
also common. The main means of transport throughout PNG
20   is by jet and light aircraft and the economy is highly
dependent on air transportation. Thus there is an urgent
need to monitor the volcanoes in New Britain (there are
many) and throughout PNG.

25   The apparatus of the preferred embodiment operates off
batteries for up to 16 hours and can be deployed in
relatively hostile environments, rapidly by a single user.
To test the ability of the instrument to distinguish ash
from other meteorological clouds, the apparatus was
30   deployed at a variety of locations and in a variety of
viewing configurations. The measurements were made in an
atmosphere with quite high water vapour amounts and at
elevation angles varying from 10° to nearly vertical
viewing. On many occasions the atmosphere around the
35   instrument was filled with ash particles, making the
atmosphere appear grey and causing irritation to the eyes
and lungs.

Results

(a) Rababa

The best results were obtained from Rababa,
approximately 1800 m from the crater. Note that there are
also water clouds 70 in the image and the high frequency
of activity has caused the atmosphere to be heavily laden
with ash particles.

Figure 15 shows a typical results obtained from Rababa
(c). The ash image (left-panel) correctly identifies the
plume 71 and clouds of ash from Tavurvur. Grey to black
coloured regions of the image are identified as having no
ash. The mountainside 72 is also identified as ash — this
is not surprising since the mountain is covered in ash
particles.

The automatic alarm algorithm was used on all images and
the alarm generated for the image shown in Fig. 15 is
shown in Fig. 16. The alarm is being generated because of
the difference between the actual histogram 210 and
threshold histogram 211. About 43% of the pixels are
identified as ash in the image and a clear and unambiguous
ash alarm has been triggered.

(b) Matupit village

Good results were also obtained from Matupit village (D)
about 2.5 km from the vent. The measurements from Matupit
were made in relatively "wet" conditions and drizzle as
well as ash fall were observed here. Results were very
similar to those obtained from Rababa. To illustrate the
ability of the apparatus to detect ash at high elevation
angles, Fig. 17 shows an ash image and corresponding
photograph of a dispersing ash cloud 75 viewed from 40°
elevation.

In this case 73% of the pixels were identified as ash (see Fig. 18).

(c) RVO

5

Ash images from RVO (E) were the most difficult to obtain because of the distance from the active vent (~8 km) and because the Observatory is perched on a hill; thus the camera could only view at relatively small elevation

10   angles (~10° or less). The combination of the greater distance and small elevation angles means that a considerable water vapour path is traversed (the water vapour absorption masks the positive temperature differences expected from the ash signal). The frequency

15   of eruption was so high that the air between the camera and the eruption column was often filled with fine ash particles. This has the effect of making the atmosphere appear grey and also causes large absorption in the infrared. The camera was operated continuously overnight

20   at RVO. An example of the scene viewed by the apparatus from RVO is shown in Figure 19.

Since the apparatus operated through the night, we were able to test the alarm algorithm without actually viewing

25   the image data. Figure 20 shows a time-series of alarms detected by the apparatus from RVO.

The series of triangles and circles 81 represent alternate 5-min sampled data and their similarity gives confidence

30   in the results.

The threshold for the alarm has been arbitrarily set to a value of 10%. In practice this will have to be amended to suit the viewing conditions. The plot suggests that there

35   were continuous ash emissions during the night – in agreement with what was observed during the day. Notice that the highest alarm percentages never exceed 35% or so

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and this is simply a function of the viewing attitude of
the instrument. If the instrument were sited closer to
the volcano, then more of the ash would fill the field of
view of the instrument and there would be a higher
5   percentage for the alarm. Again this is a feature that
need to be considered within the context of the viewing
geometry and location of the instrument with respect to
the activity.

10   Because the atmosphere around Rabaul was constantly
affected by ash it was difficult to obtain images which
showed no ash. Some data were acquired looking away from
the vent at meteorological clouds during the daytime which
suggests the instrument was working as expected. Figure
15   21 shows one of the images. In this image the
meteorological cloud is mostly light yellow or blue-green,
suggesting no ash. The pixels coloured yellow in the
bottom right of the image correspond to very low elevation
angles and ground targets that often give temperature
20   differences slightly greater than zero. The corresponding
alarm histogram was not triggered by these data (see Fig.
22).

It will be apparent to a person skilled in the art that
these and many other variations fall within the scope of
25   the present invention.